Multipath

A propagation phenomenon called multipath causes very different effects for analog versus digital television transmissions. Multipath is caused by the fact that the broadcast signal may reach the television antenna through several propagation paths that reflect off of various natural and man-made objects. A direct signal path encountering no reflections may also be present. The reflected signal paths are essentially delayed versions of the direct-path signal—with the delay being dependent on the additional distance traveled by each reflected signal.

With analog (NTSC) television, multipath causes one or more "ghost" images displaced horizontally from the main image. (The term "ghost" refers to the ghost-like appearance of the displaced image, which appears as a fainter version of the primary image.) Ghosts can significantly degrade picture quality even when the primary signal strength is quite high. In analog television, control of ghosts is usually accomplished by using a directional antenna oriented to selectively receive the stronger signal (usually the direct path signal) and to reject—at least to some extent—other paths, for which signals typically arrive from other directions.

With digital (ATSC) television, multipath does not cause ghost-like displaced images on the screen, though the term "ghost" is still used to describe multipath propagation. Instead, a weak ghost may have no effect on the picture at all. A somewhat stronger ghost may cause picture impairments such as blockiness or freeze frames. An even stronger ghost can completely prevent the television from decoding the digital data necessary to produce a picture and sound. Consequently, all ATSC television receivers contain a circuit called an equalizer, the function of which is to adaptively cancel ghosts. If the equalizer reduces the amplitudes of all but one signal path to a sufficiently low level, the picture will be displayed with no impairment at all. If the cancellation is insufficient, the TV may fail to produce a picture even when signal level is very strong.

Equalizer performance has been one of the primary areas of technological improvement as DTV receivers progress from one generation to the next. With advances in equalizer technology, significant improvements have been made in the ability to cancel larger amplitude ghosts, ghosts with larger delays relative to the main signal, and ghost signals arriving earlier than the main signal (in cases for which the direct path signal is either absent or weaker than reflected signals). Other researchers have noted a high degree of improvement in multipath-handling capability of the latest generation of equalizer technology.[*]

Consequently, a part of determining the ability of a DTV receiver to receive over-the-air signals is to characterize the ability of the receiver to handle various multipath conditions. For this study, that characterization was performed by feeding the antenna input terminal of the TV with signals that were recorded from television antennas at various locations in New York City and Washington, D.C.

It is also noted that, for DTV receivers that are compliant with the EIA/CEA-909 Antenna Control Interface specification, smart antenna technology can mitigate the effects of multipath, as well as certain other reception issues, through automatic optimization of various antenna parameters such as the effective pointing direction, polarization, and amplifier gain on a per-channel basis. The ATSC, in its "ATSC Recommended Practice: Receiver Performance Guidelines", recommends that "in addition to the other guidelines contained herein for the handling of signal conditions that are experienced in the field, consideration of a receiver-controlled antenna, as enabled by CEA-909, is recommended" and notes that such a controllable antenna can "work in conjunction with a receiver's equalizer, tuner, and demodulator to improve reception under conditions of multipath and unusually weak or strong signals."[†] This interface

[*] Laud, Tim, Aitken, Mark; Bretl, Wayne; and Kwak, K. Y., "Performance of 5th Generation 8-VSB Receivers", IEEE Transactions on Consumer Electronics, Vol. 50, No. 4, November 2004.

[†] "ATSC Recommended Practice: Receiver Performance Guidelines", ATSC Doc. A/74, Advanced Television Systems Committee, 17 June 2004, p.24.

was included in only one of the DTV receivers tested for this report. Though the smart antenna functionality was not formally tested, we observed that it did offer a user-friendly way to optimize TV reception. Not only does it simplify the initial setup of the DTV for the consumer, but it also provides the advantage of instantaneously switching the antenna pointing direction—electronically—whenever the TV channel is changed.

STANDARD FOR DETERMINING WHETHER A HOUSEHOLD IS UNSERVED

Section 73.622(e) of the Commission's rules, Code of Federal Regulations (CFR) 47, specifies a method for determining the service area of a DTV broadcast station based on OET Bulletin No. 69, *"Longley-Rice Methodology for Evaluating TV Coverage and Interference"*—hereafter referred to as OET-69. The bulletin defines the method for predicting field strength created at any given location by a television transmitter. It further defines television reception system "planning factors" that can be used to determine the field strength required for successful DTV reception.

The FCC's defined reception planning factors include antenna gain, signal loss in the down-lead cable connecting the antenna to the television receiver, noise figure of the receiver, and required carrier-to-noise ratio. The latter two factors are functions of the DTV receiver and are a primary focus of the measurements conducted for this report. These parameters, as specified by OET-69, are shown in Table 1-1.

Table 1-1. Planning Factors for DTV Reception Prediction

Planning Factor	Symbol	Low VHF	High VHF	UHF
Geometric Mean Frequency (MHz)	F	69	194	615
System noise figure (dB)	N_S	10	10	7
Required Carrier-to-Noise ratio (dB)	C/N	15.2 (15)	15.2 (15)	15.2 (15)

Note: The Final Technical Report of the FCC Advisory Committee on Advanced Television Service listed 15.19 dB as the C/N for the Grand Alliance DTV receiver.* In OET-69 this value is rounded to the nearest dB—i.e., 15 dB; however, in identifying "OET-69" planning factors and predictions for this report, we will round to the nearest tenth of a dB and use 15.2 dB. Combining this C/N value with the system noise figures and the -106.2 dBm thermal noise level specified in OET-69, yields a minimum signal power at TOV of -81.0 dBm in VHF and -84.0 dBm in UHF.

Although OET-69 was developed for defining service areas for channel-allocation purposes, the same approach could be used for initial prediction of whether a household is unserved by an adequate digital signal for SHVERA purposes. Consequently, this report will evaluate the validity of the OET-69 planning factors based on measurements of current-model consumer DTVs.

OVERVIEW

The laboratory-based measurements performed for this report emulated two types of over-the-air reception conditions for DTV receivers:

(1) Unimpaired signal (i.e., no multipath) [Chapters 3 – 5], and

(2) Signal impaired by multipath (ghosts) [Chapter 6]—focusing on particularly difficult multipath conditions.

* Final Technical Report, FCC Advisory Committee on Advanced Television Service's (ACATS), October 31, 1995, p.15 (Table 5.1).

The unimpaired signal measurements can be used to quantitatively predict receiver performance under benign reception conditions—i.e., with little multipath (commonly referred to as a white Gaussian channel). The multipath tests provide a basis for comparing the ability of different DTV receivers to handle difficult multipath conditions. Chapter 7 links the new, laboratory-based measurements to earlier FCC field-test data as a basis for anchoring the multipath results to representative, real-world reception conditions.

CHAPTER 2
SCOPE AND APPROACH

SCOPE OF TESTING

The parameters measured for this report to characterize each television receiver are as follows:
(1) minimum signal at the threshold of visibility of errors (TOV);
(2) the white noise threshold (defined at the TOV)—also known as the required carrier-to-noise ratio (CNR); and,
(3) the number of ATSC-recommended field ensembles (RF captures) that can be successfully demodulated by the receiver.

The first two of these are measures of sensitivity of the receiver for an unimpaired signal. The latter characterizes the ability of the receiver to handle difficult multipath conditions.

While these measurements provide a basis for achieving the stated objectives of this report, it should be recognized that they do not fully characterize the over-the-air reception capability of a DTV receiver. The ATSC recommends that DTV receivers be evaluated on the basis of a wide variety of criteria that are not included in this report, such as multi-signal overload, tolerance to phase noise, co-channel rejection, adjacent-channel rejection, burst noise rejection, and a more complete characterization of multipath capability.*

TEST SAMPLES

Given the objectives of determining whether there is a wide variation in reception performance of reasonably-priced consumer digital television receivers and determining whether the variation is related to price of the receiver, an effort was made to select samples over a range of prices, but with emphasis on the lower end of the price range.

Two categories of DTV receivers were acquired for this project: digital set-top boxes (STBs) and DTVs with integrated over-the-air ATSC tuners. The selected receivers are standard, off-the-shelf consumer products currently on the market.

STBs were included in the study because connection of a set-top box to an existing television represents the lowest-cost alternative for DTV reception. Each STB includes a digital tuner and outputs necessary to drive high-definition television displays (through component video, DVI, or HDMI connections) and standard-resolution analog televisions (through a composite video output or an S-Video [Y-C] output). When driving a conventional analog television, high definition programming is down-converted to the resolution of the TV. Besides their use in enabling digital reception with analog TVs, set-top boxes are also useful to consumers who have high-definition, digital-ready televisions that do not include an ATSC tuner.

* "ATSC Recommended Practice: Receiver Performance Guidelines", ATSC Doc. A/74, Advanced Television Systems Committee, 17 June 2004.

Selection Criteria

In selecting receivers for this study, several criteria were applied.

1. A total of about 30 samples was planned for the tests in order to balance the need for a large enough sample to provide a degree of statistical confidence in the results with the need to limit sample size for practical reasons.

2. Recently introduced models were selected, where possible, especially if the manufacturer expected a change in over-the-air digital reception performance with the newer model; in some cases this meant requesting a model that was not available when the tests were begun, but was delivered late in the test cycle or, in two cases, was delivered too late to include in this report.

3. An attempt was made to obtain one set-top box from most companies that manufacture one. (All set-top box models were of relatively old designs—introduced in the year 2004 or, in one case, 2003—even though they were the latest models available on the market.)

4. One DTV having an integrated ATSC tuner was selected from at or near the low-price end of each manufacturer's product line.

5. In addition, a mid or mid-to-high priced DTV having an integrated ATSC tuner was requested from many of the manufacturers.

Overview of the Samples

Table 2-1 summarizes the characteristics of the DTV receivers in the test sample. The receivers, which represent 16 brand names, are divided by product type—set-top box versus DTV with integrated ATSC tuner—and, within the DTV type, by price range. In most cases, prices were determined by selecting the median price from a FROOGLE search for each product conducted in August, 2005. Four products not found through FROOGLE were priced through Wal-Mart in August, 2005, and one was priced through Amazon in September, 2005.

Table 2-1. DTV Receiver Samples

Sample Type	Number of Samples	Display Size	Display Aspect Ratio	Display Technology
Set-Top Box (STB)	5	N/A	N/A	N/A
DTV with Integrated ATSC Digital Tuner:				
• $370 - $1000	6	26" – 36"	4:3 or 16:9	Direct-View CRT
• $1001 - $2000	8	26" – 52"	16:9	Direct-View LCD, Plasma, CRT Rear Projection, DLP Rear Projection, LCD Rear Projection
• $2001 - $4200	9	32" – 62"	16:9	Direct-View LCD, Plasma, DLP Rear Projection, LCD Rear Projection
TOTAL	28			

Notes:
--CRT = cathode ray tube (conventional picture tube)
--DLP = digital light processing
--LCD = liquid crystal display

In order to avoid revealing specific brands or models of the samples, test results presented in this document are reported by product type and price categories and by a letter and number code assigned to each product. The letter indicates product brand—with letters randomly assigned to brand names. Within each brand, a number is assigned in order of increasing price. For example, the designations A1, A2, and A3 represent three same-brand receivers listed in order of increasing price.

TEST PHILOSOPHY AND APPROACH

Laboratory Versus Field Testing

All testing was performed in the laboratory using either laboratory-generated signals or signals that had been digitally recorded from television antennas at various test sites in New York City and the Washington, DC area, and were replayed in the laboratory using equipment that allowed the signal to translated to any desired TV channel number for playback.

This test method offered two advantages over field-testing of the receivers:
(1) the cost and time required for testing was far lower for lab-based tests than for field testing, which would have required transporting the bulky, heavy TVs and test equipment to multiple sites; (the TVs alone weighed 2200 pounds and had a combined width of 82 feet), and,
(2) tests with signals that are generated or recreated (by playback) in the laboratory are expected to yield more consistent results than are field tests, in which received signal characteristics may vary significantly over the course of testing 28 receivers.

TV Channel Selection

For testing minimum signal at TOV, channels 3, 10, and 30 were selected to represent the low-VHF, high-VHF, and UHF bands, respectively. Selection was based on relatively central locations within the respective bands and an absence of local TV broadcasts on these channels.

Other tests, for which results were not expected to vary with channel, were performed on TV channel 30.

Operation and Connection of Samples

For receivers having multiple antenna inputs that could handle ATSC signals, only the input labeled "antenna A" or "antenna 1" was tested. For receivers having a radio frequency (RF) output associated with the selected antenna input, the output was externally terminated in 75 ohms.

Each set-top box was operated in a high definition mode and was connected to a high definition monitor by means of a component video output.

Test Configurations

All test and measurement setups maintained a 50-ohm impedance throughout, except at the signal source and the consumer TV inputs, which were each specified to be nominally 75 ohms. (An older, instrumented reference receiver included in one test had a 50-ohm input impedance.) The 75-ohm devices were matched to the rest of the test setup through impedance-matching pads, except that, for one of the test setups, an impedance transformer was used at the signal source to reduce losses. In addition to the impedance-matching pads, 50-ohm attenuator pads were used at various places throughout the test setups to reduce the effects of any impedance mismatches at places where such mismatches were considered likely or would be expected to have a significant impact.

The minimum signal at TOV is the only measured parameter for which absolute accuracy of the measurement equipment was a factor; consequently, that parameter was tested by connecting a signal source—through appropriate pads, step attenuators, and cables—to one TV at a time. After adjusting the signal attenuation to achieve TOV on the TV, the output of the entire setup—with the exception of the final impedance-matching pad, was connected to a vector signal analyzer for measurement of the signal level. The only correction then necessary to determine the input to the TV was to subtract the attenuation of the impedance-matching pad from the measured level. That attenuation was measured separately.

For the measuring white noise threshold (required CNR), absolute measurement accuracy was less critical since the value to be determined was the ratio of a signal level to a noise level. To maintain accuracy of the ratio, both measurements were made with the vector signal analyzer on the same amplitude range. The reduced criticality of absolute measurement accuracy enabled the use of a splitter to simultaneously deliver the signal and noise to as many as eight TVs and to the vector signal analyzer for the quantitative measurements. The simultaneous connection reduced measurement time by allowing TV channel scans (required by many of the TVs when a signal was changed) to be performed simultaneously on multiple TVs and by reducing the need to repeatedly disconnect and reconnect cables.

Tests of the ability of each receiver to handle the multipath conditions represented by the ATSC-recommended field ensembles (RF captures) also did not require absolute accuracy in measuring the applied signal levels; consequently, the same splitter arrangement was used. The approach was to apply a signal level well above the minimum signal level at TOV (by about 50 dB) so that signal level was not an issue.

Details on the test methods and configurations are presented in Appendix A.

Thresholds

For both types of threshold measurements (required CNR and minimum signal at TOV), the reported value is the level measured on the maximum attenuation step (lowest signal level) that resulted in no observed errors in 60 seconds of viewing time. The threshold level at which the 60-second viewing time condition was met was nominally somewhere between that reported level and the next higher attenuation level (next lower signal level step); consequently, this approach can be expected to overestimate required signal levels by an average of half the attenuator step size of 0.1 dB. One could therefore justify subtraction of 0.05 dB from the measured signal levels. This subtraction was not performed, in part to compensate for the fact that TOV measurements are often based on longer observation times than the 60 seconds used in these tests.

CHAPTER 3
WHITE-NOISE THRESHOLD MEASUREMENTS (REQUIRED CARRIER-TO-NOISE RATIO)

White-noise threshold refers to the ratio of signal ("carrier") power to noise power within the 6-MHz bandwidth of a television channel when both an unimpaired signal (no multipath) and broadband ("white") Gaussian noise are simultaneously applied to the antenna terminal of a DTV receiver and the signal or noise power is adjusted to the point at which observable errors in the DTV picture just become invisible—i.e., the threshold of visibility (TOV). This is the carrier-to-noise ratio (CNR) required to produce a "clean" DTV picture. The definition assumes that the applied noise power is sufficiently higher than any noise generated internally by the DTV receiver circuitry so as to make the internally generated noise negligible.

At CNR levels below the white-noise threshold, picture quality rapidly degrades to the point that, only about one dB below the white-noise threshold, the picture is typically unwatchable or nonexistent.

At CNR levels above the white-noise threshold, the picture is essentially free of defects that are related to transmission and reception of the signal.

White noise threshold is of direct interest because it indicates the ability of a digital television to receive and process a DTV signal in the presence of high ambient noise levels—assuming that the signal is not significantly impaired by multipath or interference and that the ambient noise has characteristics similar to white Gaussian noise. In cases where the ambient environment is quiet, white noise threshold is useful in understanding the reception performance of a DTV receiver in the presence of noise that is internally generated within the input circuits of the receiver.

The results of this chapter apply only to signals that are unimpaired by multipath. In the presence of multipath, a higher CNR may be required to produce a clean picture. While the measurements performed for this report do not address such an increase, the topic is discussed in Chapter 7, based on earlier field test results.

MEASUREMENT METHOD

White-threshold of each receiver was measured by simultaneously injecting into the antenna port of the receiver both an unimpaired (e.g., no multipath) ATSC signal on channel 30 and white noise from a noise generator. A nine-way splitter feeding equal-length, well-shielded, low-loss cables allowed the same combination of signal plus noise to be applied simultaneously to as many as eight DTV receivers and a vector signal analyzer that was used for the measurements. As a consistency check, receiver D3 was included in each group of eight receivers that were tested; measurements of D3 were consistent within ±0.1 dB.

Impedance-matching attenuator pads (50 ohms to 75 ohms, 5.8 dB power attenuation) at each TV receiver served to match the nominal 75-ohm impedance of the receiver antenna ports to the rest of the 50-ohm measurement system and, through the attenuation it provided, served to reduce the impact of any deviations from that nominal TV input impedance. At the vector signal analyzer, a 6-dB, 50-ohm attenuator served a similar function.

Because the small differences in loss between the various splitter outputs, cables, and pads can be expected to equally affect both the signal and the noise, the measured CNR is not affected by such differences.

The signal source for these tests was an RF player (Sencore RFP-910) playing the "Hawaii_ReferenceA" file supplied with the player. The file consisted of a 25-second repeating loop of motion video scenes shot at several outdoor locations. At each loop restart, most DTV receivers exhibited video errors related to re-locking to the signal; consequently, the first three seconds of each loop were not included in the observation time. (An ATSC signal generator, rather than the RF player, had been intended for these tests. Use of the generator would have avoided issues with loop restart time, but the generator was abandoned due to degraded signal quality.) The signal was amplified before splitting it. A step attenuator following the amplifier was used to adjust the signal level.

The noise source was a noise generator (Noise/Com UFX-7110) band limited to 700 MHz, well above the frequency of TV channel 30, thus leaving the spectrum flat across the bandwidth of the selected TV channel. The injected noise power was set nominally to -70 dBm within the 6-MHz bandwidth of channel 30—about 29 dB above the internally generated noise of a typical DTV receiver—by using a step attenuator with 0.1-dB steps. The noise power measurement (usually within 0.05 dB of -70 dBm) was then recorded. The actual injected noise power was computed by subtracting the effect of instrument noise, which was about 26 dB below the injected noise power.

Signal level was increased in 0.1-dB steps until the TV picture could be viewed for 60 seconds without observing a video error (excluding loop restart periods, as noted above). A measurement was then made of the combined power of both the injected signal and the injected noise, and the signal power was computed by subtracting the noise power (in linear power units); since the noise power at the threshold was typically about 15 dB below the signal, the net signal power was only about 0.1 dB below the measured total power.

Further details on the measurement procedure are contained in Appendix A.

FORMAT OF THE BAR GRAPH DATA

The measurement results are presented in bar-graph form in Figure 3-1. That format, explained here, is also used in subsequent chapters to present other results.

Each bar on the graph represents performance of one DTV receiver. The "Better"/"Worse" labels on the vertical axis indicate that, for the plotted parameter, lower values represent better performance.

Each receiver is designated by a letter and a numeral. The letters, which were assigned randomly, represent brand names. Thus, receivers A1, A2, and A3 are all of the same brand.

The receivers are grouped into categories. The first category is set-top boxes (STBs). The remaining categories are three different price ranges of DTVs. Within each group, the results are listed in order of the randomly assigned brand code letters rather than in price order. This approach was taken so that individual products could not be identified based on price.

The solid blue line represents the median result across all tested receivers. The dashed blue line represents the median result within each category. The dashed red line represents the mean result within each category. A wider dashed green line represents the value of the planning factor assigned to the measured parameter by OET-69.

RESULTS

The results of the white-noise threshold measurements are shown in Figure 3-1.

Nominal Performance and Variation Among Samples

Statistics of the white-noise threshold (required CNR) are shown in Table 3-1. The white noise threshold of the median receiver—measured across all tested receivers—is 15.3 dB. This is only 0.1 dB above (worse than) the corresponding planning factor value in OET-69. (Because the CNR was determined from the ratio of two power measurements performed on the same amplitude range of the same measuring instrument, it's value is not affected by absolute calibration accuracy of the instrument and is therefore expected to be accurate to within 0.2 dB.*)

Table 3-1. Statistics of White Noise Threshold

WHITE NOISE THRESHOLD	
Median across all receivers (dBm)	15.3
Median re OET-69 planning factors	0.1
Deviations of receivers from median (dB)	
--Best performing receiver (dB)	-0.4
--Worst performing receiver (dB)	0.5
--89th percentile receiver (dB)	0.3
Standard deviation (dB)	0.2
Total span from best to worst receiver (dB)	0.8†

The variations among receivers were quite small. The standard deviation of the CNR measurements across all receivers was 0.2 dB. The total span from best to worst performing receiver was 0.8 dB, with the worst measured white noise threshold being 0.5 dB above the median value.

Variation with Price and Type Category

Magnitude of Observed Variations With Product Type and Price

The observed performance variations among the product type and price categories were also small, as shown in Table 3-2. The least expensive way to receive a DTV broadcast is to purchase a digital set-top box and connect it to an existing TV. Median performance of set-top boxes was only 0.1 dB worse than the overall median. The median low-cost and mid-cost DTVs performed at the overall median, and the median high-cost DTV performance was 0.2 dB better than the overall median.

* The vector signal analyzer specification sheet states that relative accuracy in RF vector mode on a single range is the sum of frequency response and amplitude linearity. If we ignore the frequency response term because the measurements are made over the same frequency range, we are left with the amplitude linearity term, which is specified as "<0.1 dB" for signal levels between 0 dB and -30 dB with respect to full scale—a condition that was met by both the signal and injected noise measurements. To this we add errors caused by the 0.1-dB attenuator step size.

† Span does not match difference between worst and best due to rounding of all numbers to nearest 0.1 dB.

Table 3-2. Product-Type/Price Variations of White Noise Threshold

WHITE NOISE THRESHOLD	
Median of Set-Top Boxes re Overall Median (dB)	0.1
Median of Low-Price DTVs re Overall Median (dB)	0.0
Median of Medium-Price DTVs re Overall Median (dB)	0.0
Median of High-Price DTVs re Overall Median (dB)	-0.2

Statistical Significance of Observed Variations With Product Type and Price

Apparent variations in performance of samples with price can be caused by random sampling effects even when there is no underlying performance/price dependence in the overall population; hence, some means is necessary to determine whether an apparent dependence observed in the sample is statistically significant.

In the case of measurements of the required CNR for the tested collection of DTV receivers, the observed variations with price are so small as to be inconsequential; consequently, assessing the statistical validity of those variations is hardly necessary. Nonetheless, an analysis is included here for completeness and to provide a comparative basis for more significant observed variations that are presented in subsequent chapters.

As seen in Table 3-3, the Pearson's correlation coefficient between required CNR and receiver price was computed as -8.6 percent when all receivers were included and +7.0 percent when only the DTVs (not set-top boxes) were included. A negative sign indicates that the required CNR appears to decrease (i.e., improve) with increasing receiver price, while a positive sign indicates that the required CNR increases (i.e., degrades) with increasing price. Determining whether any observed apparent trend is real or is an artifact of the small sample set used in the tests requires a statistical assessment.

Table 3-3. Correlation Coefficient of White Noise Threshold with Price

Pearson's Correlation Coefficient of White Noise Threshold with Price	
All Tested Receivers	-8.6%
DTVs Only (no Set-Top Boxes)	+7.0%

The usual method of assessing the statistical significance of given value of the Pearson's correlation coefficient is to compare the magnitude of the observed correlation to values in a table of critical values of the Pearson's correlation coefficient. The technique is used to determine the likelihood that a correlation as high as that which was observed might occur randomly, for the selected sample, if there is no actual correlation between required CNR and receiver price in the larger population of all DTV receivers. Such a lookup table specifies values as a function of the "number of degrees of freedom", which is two less than the total number of samples—*assuming that the samples are independent.*

For the overall sample size used in this study (28 samples, 26 degrees of freedom), one can determine from such a table that the magnitude of an observed correlation coefficient must be 32 percent or higher in order to ensure that there is no more than a five percent probability that the observed correlation could result by random sampling effects from a larger population that has no such correlation. In the case of the 23 DTVs (i.e., excluding the set-top boxes), the magnitude of an observed correlation would have to be 35 percent or higher to meet the same criterion. (These are single-sided probabilities—i.e., the probability that a correlation magnitude will exceed, in a single direction, a given correlation value. For example, if the overall population has no correlation with price, there is a five percent probability that the correlation of a randomly selected sample of 28 receivers will exceed a 32 percent magnitude with a negative correlation—indicating decreasing CNR with increasing receiver price. There is also a five percent probability of exceeding that same magnitude with a positive correlation—indicating increasing CNR with increasing price.)

It should be noted that these statistical calculations are dependent upon a number of assumptions, including that the shape of the probability distribution of the measured parameter is normal (Gaussian), that the samples were randomly selected, and that the samples are independent. None of these assumptions is strictly true for the case at hand. Of particular concern is the independence assumption, because it is quite likely that some of the receiver samples share critical subsystems. For example, a given tuner or demodulator design may be used in more than one of the receivers. The effect of such a commonality between samples would be to decrease the effective number of degrees of freedom in the computed Pearson's correlation coefficient. Such a decrease would increase the magnitude of correlation that would have to be observed to have a given confidence level in the result.

The observed correlations of -8.6 percent and +7.0 percent in the white-noise threshold measurements are so small as to provide no confidence that the small observed variations in performance with price reflect a real price-dependence in the overall population of DTV receivers currently on the market.

Effect of TV Channel

White noise threshold (required CNR) is expected to be dependent on the demodulator function of a DTV receiver. Since this function occurs after the tuner heterodynes the incoming RF signal from the frequency band of the TV channel to an intermediate frequency (IF), one would expect the white noise threshold to be essentially independent of TV channel number. Consequently, testing was performed on only one channel—channel 30.

In testing minimum signal level of the DTV receivers, as reported in the next chapter, there was a large variation in the results between channels for some TVs. In order to verify that the variation was not related to changes in white noise threshold, the white noise threshold of one DTV receiver was also tested on channel 3. The selected receiver was G2, the receiver with the largest variation in minimum signal level across the channels (a 13 dB difference between channels 3 and 30). For this receiver, the measured white noise thresholds on channels 3 and 30 were 15.6 and 15.5 dB, respectively; this difference is within measurement error.

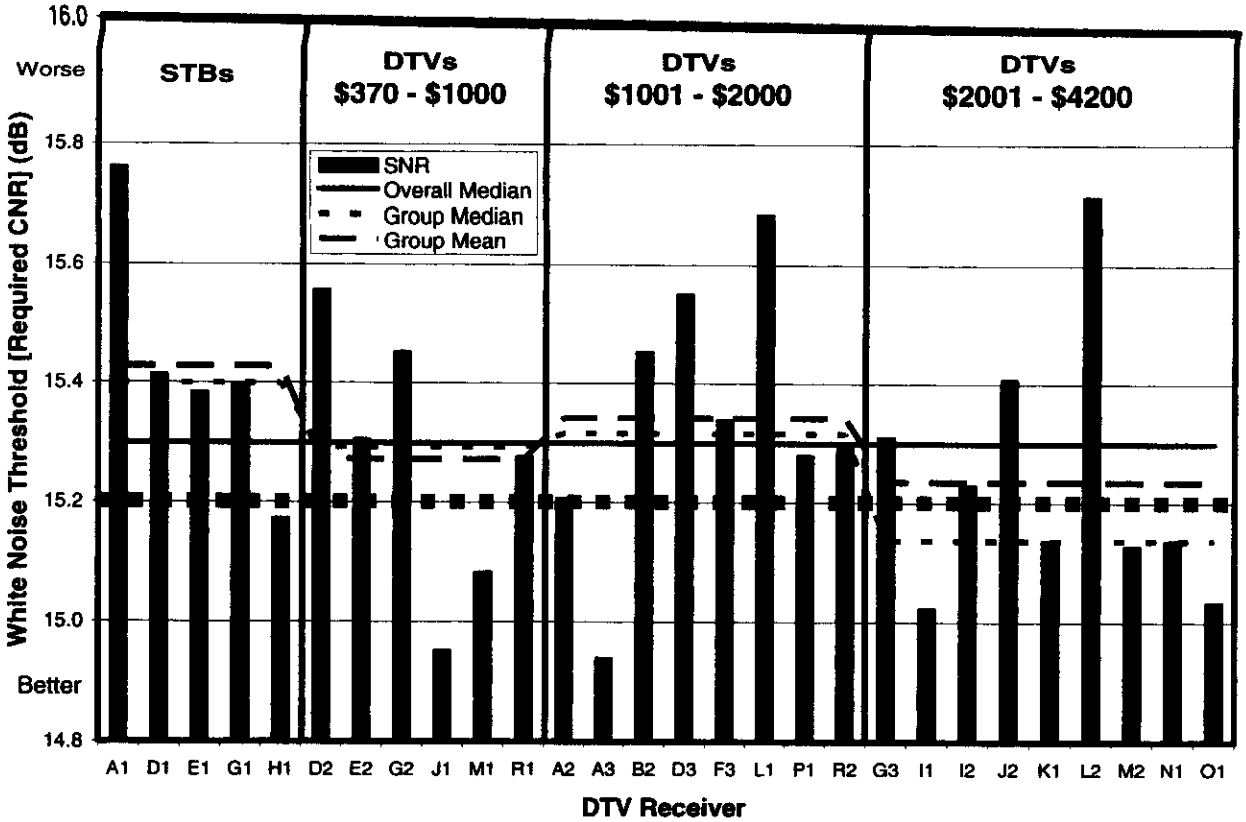

Figure 3-1. Measured White Noise Threshold of Receivers

CHAPTER 4
MINIMUM INPUT SIGNAL MEASUREMENTS

Minimum input signal at the threshold of visibility (TOV) is the signal ("carrier") power at the antenna terminal of a DTV receiver when the signal level is adjusted to the point at which observable errors in the DTV picture just become invisible. It is a direct measure of sensitivity of a DTV receiver to weak signals in the absence of significant externally generated noise or interference—assuming that the input signal is not significantly impaired by multipath. At input levels below this threshold level, picture quality rapidly degrades to the point that, only about one dB below the white-noise threshold, the picture is typically unwatchable or nonexistent. At input levels above the threshold, the TV picture is essentially free of defects that are related to transmission and reception of the signal.

The results of this chapter apply only to signals that are unimpaired by multipath or interference. In the presence of multipath, a higher signal level may be required to produce a clean picture. While the measurements performed for this report do not address such an increase, the topic is discussed in Chapter 7, based on earlier field test results.

MEASUREMENT METHOD

Because minimum input signal at TOV is an absolute measurement rather than a ratio, the splitter was not used for these tests. The receivers were tested sequentially in groups of about eight—with receiver D3 included in each group, as a consistency check; measurements of D3 were consistent within ±0.3 dB. The results are subject to the absolute measurement accuracy of the vector signal analyzer, which is specified as ±1.5 dB maximum and ±0.5 dB typical on the amplitude range that was used for the measurements;* additional errors due to adjustment for attenuation of impedance-matching pad—as described below—are expected to be negligible compared to the VSA tolerance.

The tests were performed on three TV channels—3, 10, and 30—in order to evaluate performance in the low VHF, high VHF, and UHF bands, respectively. The selection of those specific channels was based on avoiding local broadcast channels and selection of a relatively central channel within each band.

The signal source for these tests was an RF player (Sencore RFP-910) playing the "Hawaii_ReferenceA" file supplied with the player. The file consisted of a 25-second repeating loop of motion video scenes shot at several outdoor locations. At each loop restart, many DTV receivers exhibited video errors related to re-locking to the signal; consequently, the first three seconds of each loop were not included in the observation time. A step attenuator was used to adjust the signal level. The signal was applied to a single DTV receiver through a low-loss 50-ohm cable followed by a 10-dB attenuator pad and an impedance-matching attenuator pad having 5.8 dB power attenuation. The latter served to match the nominal 75-ohm impedance of the receiver antenna port to the rest of the 50-ohm measurement system. Both pads served

* As an additional check on equipment performance, measurements of injected broadband signal level and of injected broadband noise level—at levels typical of those used for white-noise threshold testing (-70 dBm for noise and -55 dBm for signal—both measured across the 6-MHz bandwidth of TV channel 30)—were performed using two instruments, the vector signal analyzer and a spectrum analyzer (Agilent E7405A). The spectrum analyzer measurements were made with the internal preamp on and the internal attenuation set to 0 dB. The spectrum analyzer overall amplitude accuracy is specified as "±(0.54 dB + absolute frequency response)" with the absolute frequency response being specified as ±0.5 dB over the frequency range of interest. For both signal and noise, the spectrum analyzer measurements were 0.1 dB higher than the vector signal analyzer measurements—suggesting that both instruments (which were calibrated no more than two months before the measurements reported in this chapter) were likely performing well within the specified tolerances. (Note that self calibrations were also performed on both instruments before each set of measurements.)

to minimize reflections that might be caused by any deviation of receiver input impedance from the nominal.

Signal level was increased in 0.1-dB steps until the TV picture could be viewed for 60 seconds without observing a video error (excluding loop restart periods, as noted above). The low-loss cable and 10-dB pad were then connected to a vector signal analyzer on its most sensitive amplitude range (-50 dBm) to measure the power of the applied signal. The 10-dB pad served to minimize reflections that would be caused by any deviation of the vector signal analyzer input impedance from 50 ohms. A separate measurement of instrument noise (typically about 19 dB below the measured signal level) was subtracted—in linear power units—from the measured power level to remove the very minor effects of vector signal analyzer self noise from the measurement. The attenuation of the impedance matching pad, which was connected to the TV input but not to the vector signal analyzer, was then subtracted (in dB) from the result to determine the signal level that had been applied to the DTV receiver antenna port. The presence of that pad at the TV input but not at the spectrum analyzer input served a dual purpose—matching the respective input impedances of the two devices and providing a 5.8 dB signal advantage to the vector analyzer to minimize the impact of the vector signal analyzer self noise.

Further details on the measurement procedure are contained in Appendix A.

RESULTS

The results of the minimum signal level measurements for the three tested channels are shown in Figure 4-1. Individual results for TV channels 3, 10, and 30 are shown in Figures 4-2, 4-3, and 4-4, respectively. The general format of the plots is as described in Chapter 3 in the section titled, "Format of the Bar Graph Data", except that, in the case of Figure 4-1, there are three bars per DTV receiver—representing the three channels tested. Also, note the differences in vertical scales among the four graphs.

Nominal Performance and Variation Among Samples

Table 4-1 shows the statistical properties of the measurements of minimum signal level at TOV.

Table 4-1. Statistics of Minimum Signal Level at TOV

MINIMUM SIGNAL LEVEL AT TOV	Chan 3	Chan 10	Chan 30
Median across all receivers (dBm)	-82.2	-83.2	-83.9
Median re OET-69 planning factors	-1.2	-2.2	0.1
Deviations of receivers from median (dB)			
--Best performing receiver (dB)	-2.5	-1.7	-1.4
--Worst performing receiver (dB)	12.5	4.3	2.5
--89th percentile receiver (dB)	5.1	3.1	1.3
Standard deviation (dB)	3.7	1.6	0.9
Total span from worst to best receiver (dB)	15.0	6.0	3.9

The median minimum signal level at TOV across all measured receivers was found to decrease slightly with increasing channel number—with channel 3 requiring a 1.7-dB higher signal than channel 30. The measured median values match—within 1 dB—the -83 dBm minimum performance standard recommended by the ATSC.*

* "*ATSC Recommended Practice: Receiver Performance Guidelines*", ATSC Doc. A/74, Advanced Television Systems Committee, 17 June 2004, p.11.

The median required signal levels were slightly better—by 1.2 dB and 2.2 dB, respectively—than that predicted for the VHF-low and VHF-high bands using the OET-69 planning factors (-81.0 dBm) and closely matched the predictions for channel 30 (-84.0 dBm).* On channel 3, only 21 percent of the tested receivers performed more poorly in minimum signal level than the performance modeled in OET-69 by an amount exceeding 1-dB—the approximate tolerance of the measurements.† On channels 10 and 30, the numbers are 11 percent and 18 percent, respectively.

The variation among receivers was large on channel 3—with a 3.7-dB standard deviation. The two receivers exhibiting poorest performance performed at levels 10.6 and 12.5 dB worse than the median. Those two receivers—both the same brand—are responsible for much of the observed variability; omitting them from the calculations reduces the standard deviation to 2.3 dB. The third worst performer was 6.7 dB above the median. 89 percent of the receivers (all but three) were within 5.1 dB of the median.

Variations were relatively small on channels 10 and 30. Standard deviation across all receivers was 1.6 dB on channel 10 and 0.9 dB on channel 30. The worst performers differed from the median by 4.3 and 2.5 dB, respectively, on channels 10 and 30, and 89 percent of the receivers (all but three) were no more than 3.1 dB above (worse than) the median on channel 10 and no more than 1.3 dB above (worse than) the median on channel 30.

Variations With TV Channel For One Sample

At least two TVs exhibited a much larger than expected variation in reception performance—as measured by minimum signal level at TOV—between the three tested TV channels. In order to further characterize this variation, the receiver exhibiting the largest variation between channels (receiver G2) was further tested to determine minimum signal at TOV for each of the 12 VHF channels and for three UHF channels. The results, shown in Figure 4-5, indicate that the receiver exhibits poor sensitivity throughout the low-VHF band (channels 2 through 6), but good sensitivity throughout the high-VHF band (channels 7 through 13) and the UHF band. On average, the high-VHF and UHF performance is 13 dB better than the low-VHF performance. The reason for this performance difference is not known.

The apparently abrupt change in sensitivity occurring between channels 6 and 7 is easier to understand if the data is plotted as a function of frequency, as in Figure 4-6. It can be seen that there is a large gap in frequency between TV channels 6 and 7, and that the increase in minimum signal at TOV that occurs in moving from the high-VHF band (channels 7-13) to the low-VHF band (channels 2-6) appears to actually begin, to a small degree, in the lower portion of the high-VHF band. (Note that the measured data is indicated by square symbols and measured points are connected by straight lines.)

Variation with Price and Type Category

Magnitude of Observed Variations With Product Type and Price

As can be seen in Table 4-2, the observed variations in minimum signal level at TOV with product type and price categories were very small for channels 10 and 30 (category medians differing from overall median by less than 1 dB) and were somewhat larger for channel 3. On channel 3, median performance of set-top boxes was 2.0 dB worse than the overall median of all receivers and the best median

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* See note for Table 1-1.

† Absolute measurement accuracy of the vector signal analyzer on the amplitude range that was used for the measurements was as ±1.5 dB maximum and ±0.5 dB typical.

performance was achieved by the low-price DTV category, which slightly outperformed the medium and high-priced categories. Most of the differences in median values between categories are so small as to be considered insignificant, and even the largest differences would influence reception performance only in locations where the signal margin is very small.

Table 4-2. Product-Type/Price Variations of Minimum Signal at TOV

MINIMUM SIGNAL LEVEL AT TOV	Chan 3	Chan 10	Chan 30
Median of Set-Top Boxes re Overall Median (dB)	2.0	0.5	0.7
Median of Low-Price DTVs re Overall Median (dB)	-1.1	-0.2	-0.2
Median of Medium-Price DTVs re Overall Median (dB)	0.0	0.5	0.0
Median of High-Price DTVs re Overall Median (dB)	-0.7	-0.3	0.0

<u>*Statistical Significance of Observed Variations With Product Type and Price*</u>

Table 4-3 shows the Pearson's correlation coefficient between the minimum signal at TOV and the price of each DTV receiver. Random sampling effects can lead to apparent correlations in a given collection of DTV receivers even if the overall DTV population of receivers on the market exhibits no such correlation; consequently, a statistical assessment must be performed in order to judge whether the observed correlation reflects an actual correlation in overall population or is simply an artifact of sampling.

Table 4-3. Correlation Coefficient of Minimum Signal at TOV with Price

Pearson's Correlation Coefficient of Minimum Signal at TOV with Price	Chan 3	Chan 10	Chan 30
All Tested Receivers	-14.3%	-4.9%	+3.9%
DTVs Only (no Set-Top Boxes)	-0.3%	+0.4%	+12.3%

Chapter 3 explains the methods and pitfalls of such a statistical assessment. Using typical assumptions, one would conclude that an observed correlation coefficient with a magnitude of 32 percent or higher is unlikely to occur (less than five percent probability) in a sample size of 28 (the total number of receivers tested for this report) if there is no correlation in the overall population. Similarly, with a sample size of 23 (the number of DTVs—excluding set-top boxes—tested for this report), a correlation coefficient magnitude of 35 percent or higher is unlikely to occur if there is no correlation in the overall population. Thus, we would conclude that an observed correlation is statistically significant only if its magnitude exceeds the appropriate one of these thresholds.*

None of the price/performance correlations found here come even close to the threshold for statistical significance. Thus, the measurements of minimum signal at TOV show no statistically significant correlation of performance with price.

* As is explained in Chapter 3, the statistical assessment performed above is dependent upon a number of assumptions that are not strictly true for the case at hand. Arguably, the most questionable of these is the assumption that the performance of the each receiver sample is independent of the others. It is quite likely that some of the receiver samples share critical subsystems, which would violate the independence assumption. For example a given tuner or demodulator design may be used in more than one of the receivers. The effect of such a commonality between samples would be to decrease the effective number of degrees of freedom in the computed Pearson's correlation coefficient. Such a decrease would increase the magnitude of correlation that would have to be observed to have a given confidence level in the result. Taking this effect into account would further diminish any statistical significance of the results.

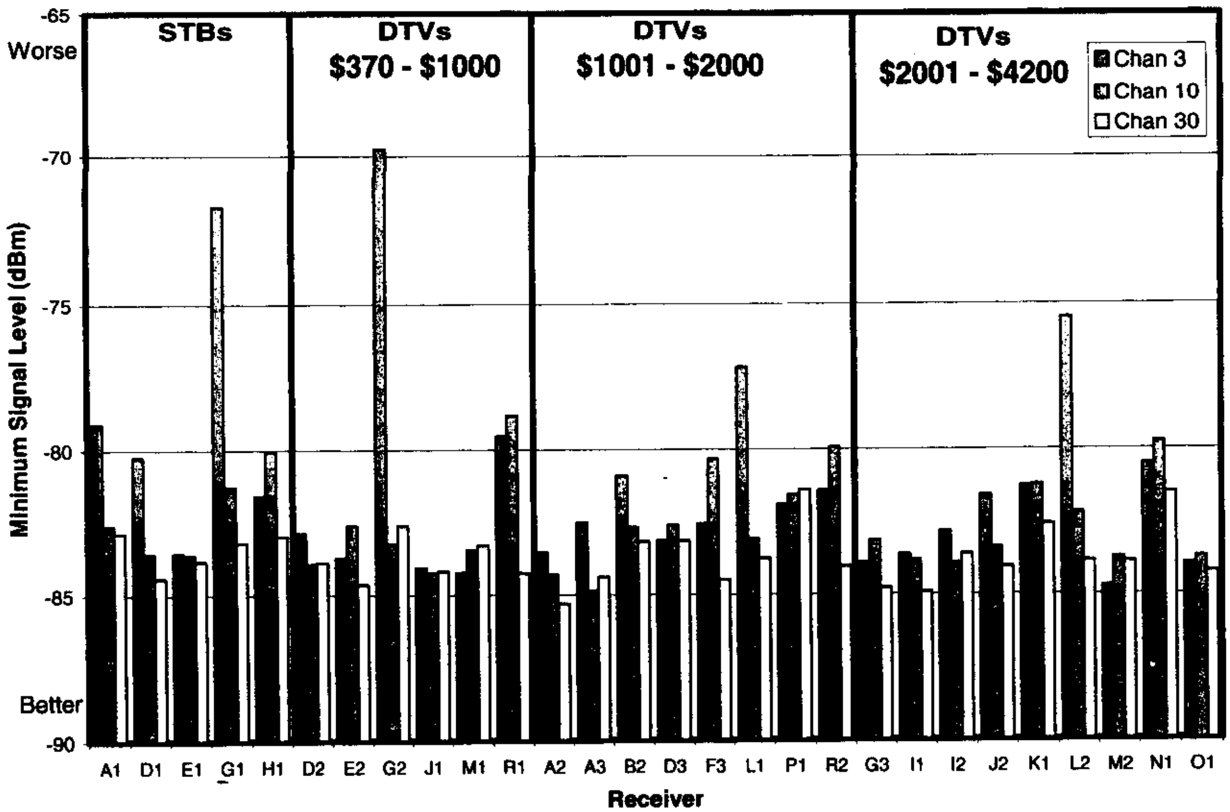

Figure 4-1. Measured Minimum Signal Level at TOV on Three Channels

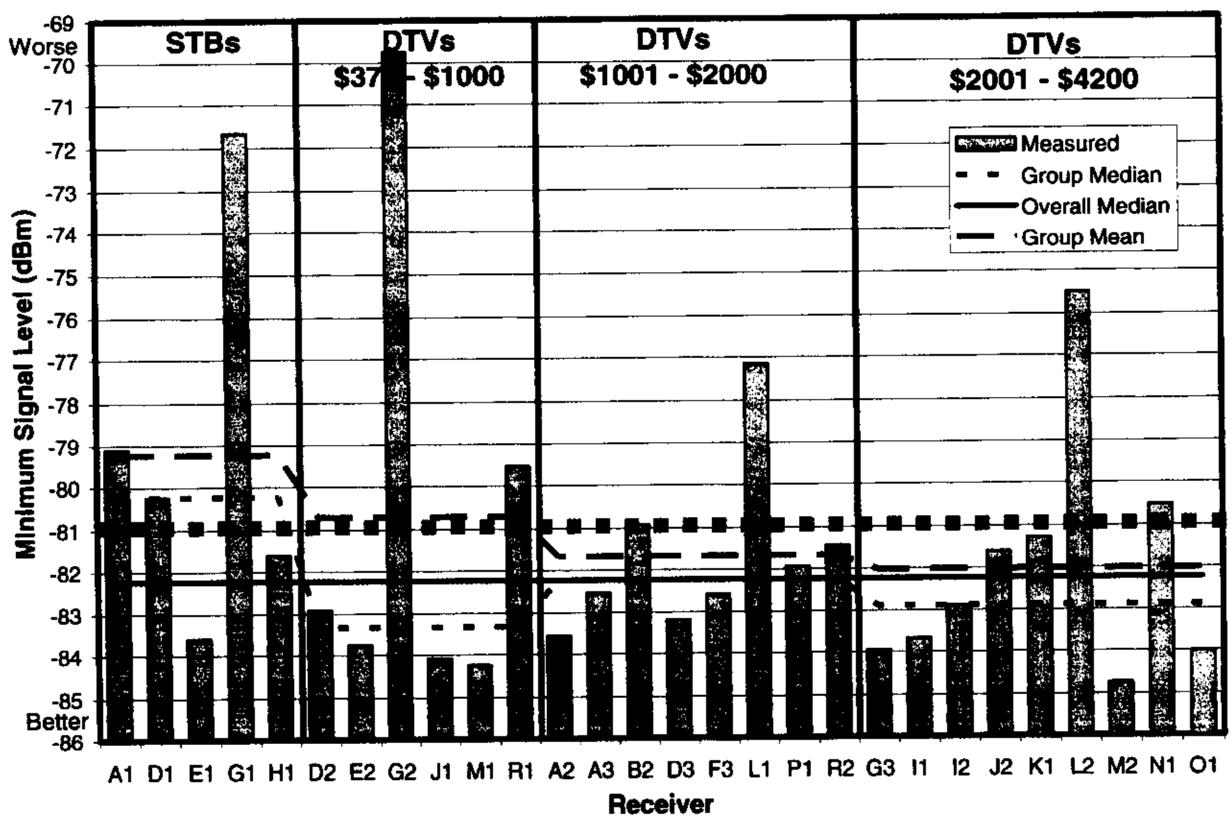

Figure 4-2. Measured Minimum Signal Level at TOV on Channel 3 (Low VHF)

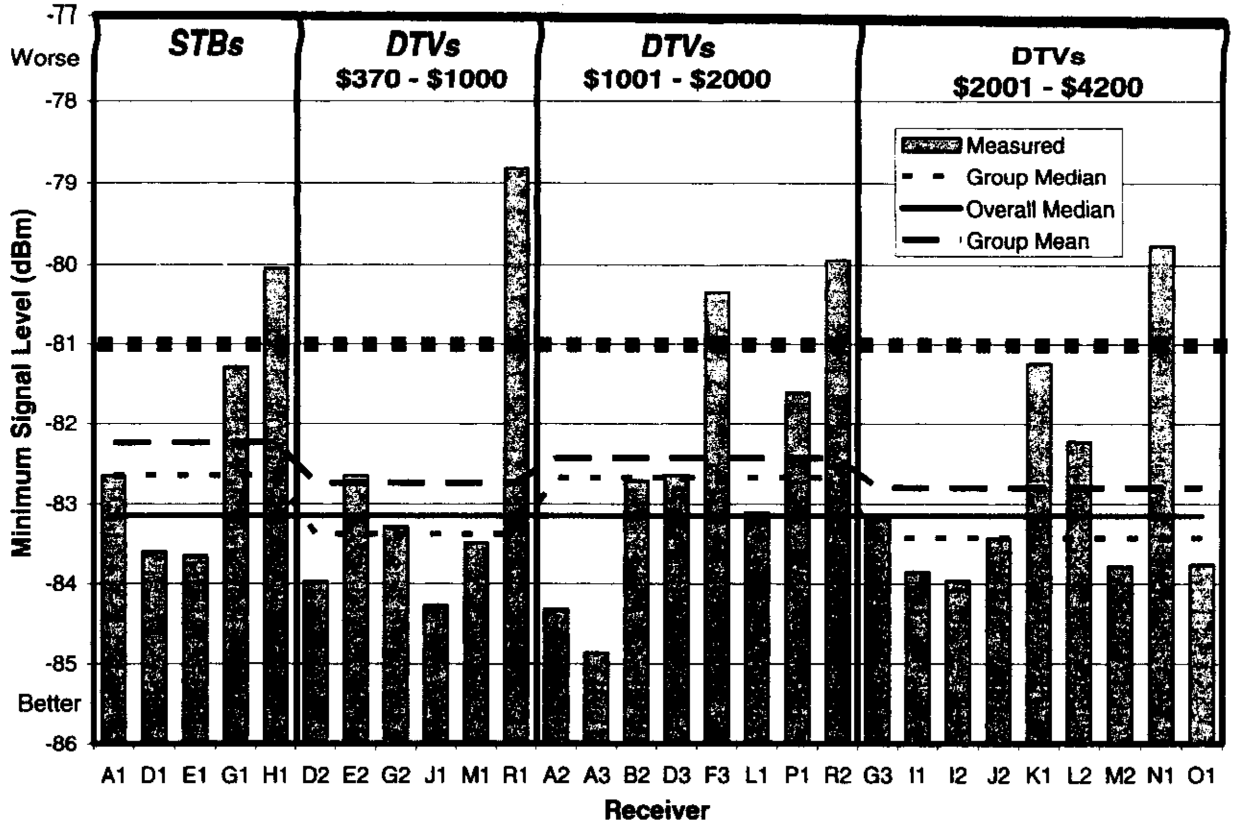

Figure 4-3. Measured Minimum Signal Level at TOV on Channel 10 (High VHF)

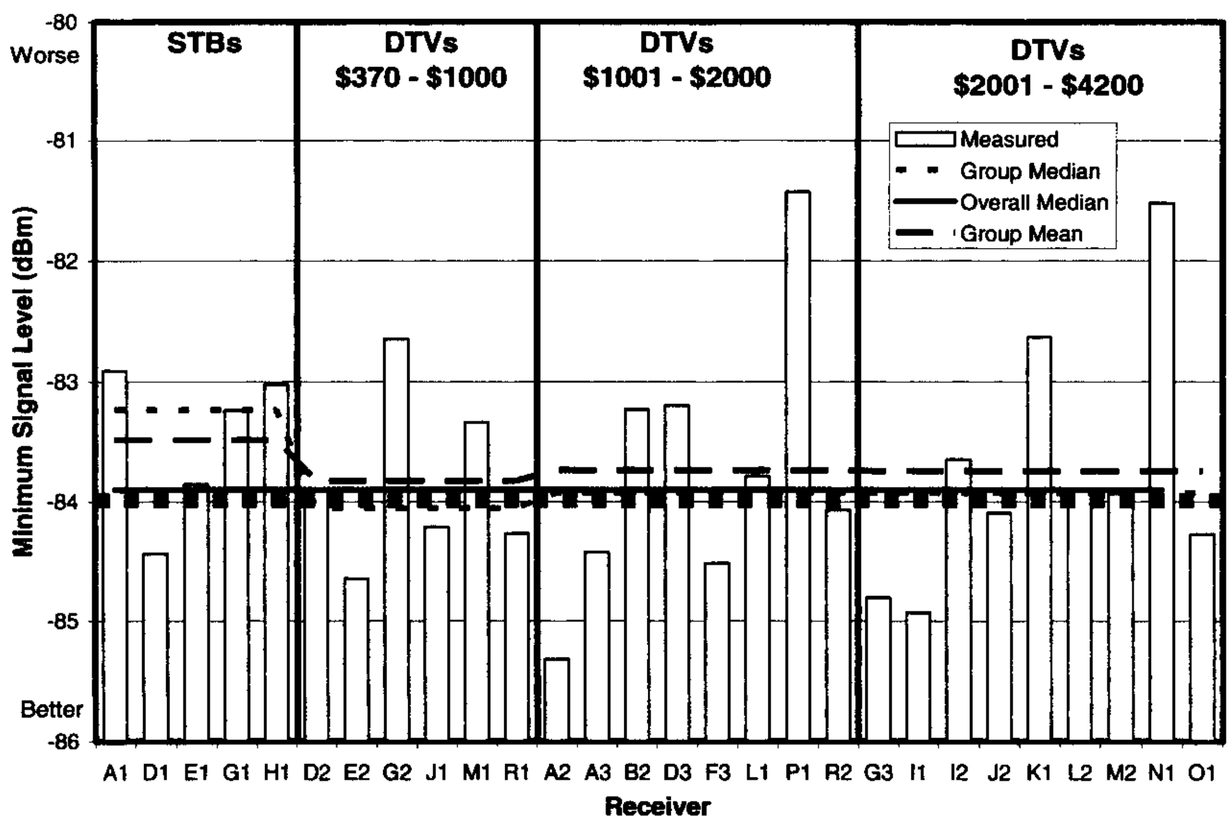

Figure 4-4. Measured Minimum Signal Level at TOV on Channel 30 (UHF)

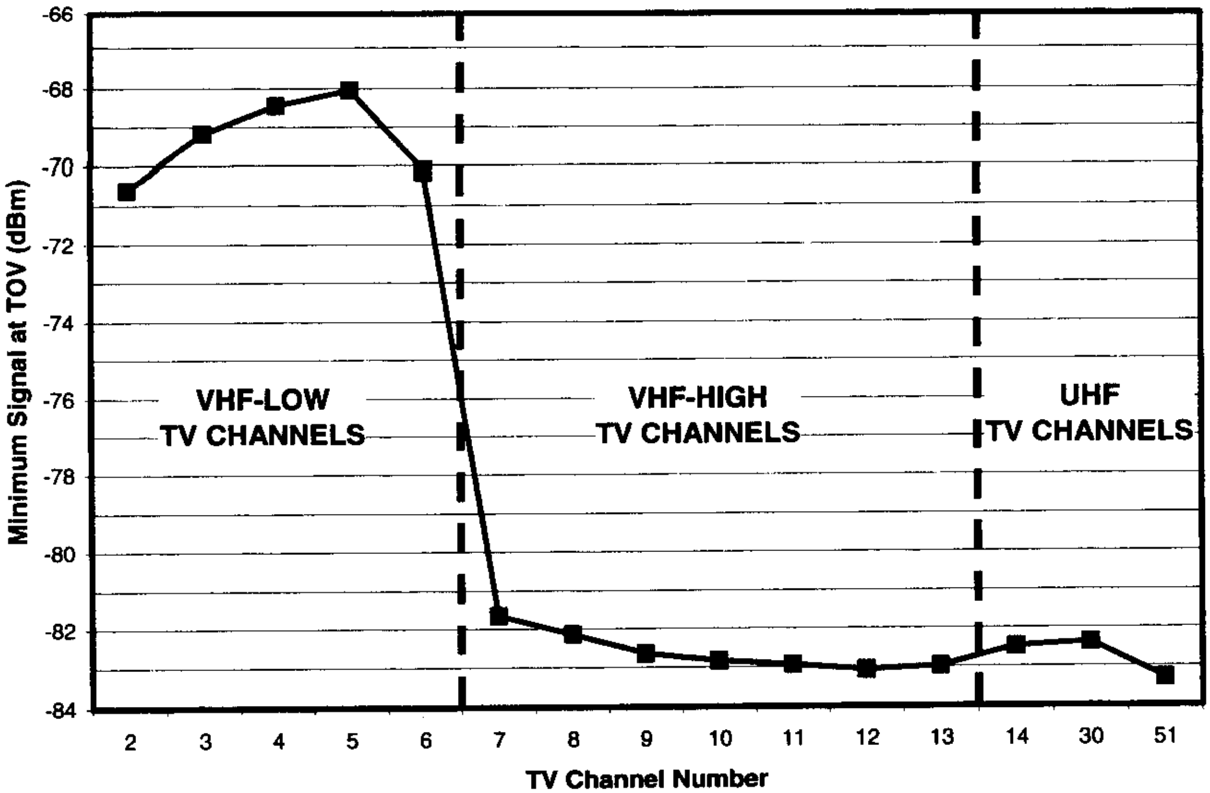

Figure 4-5. Measured Minimum Signal Level at TOV Versus Channel for Receiver G2

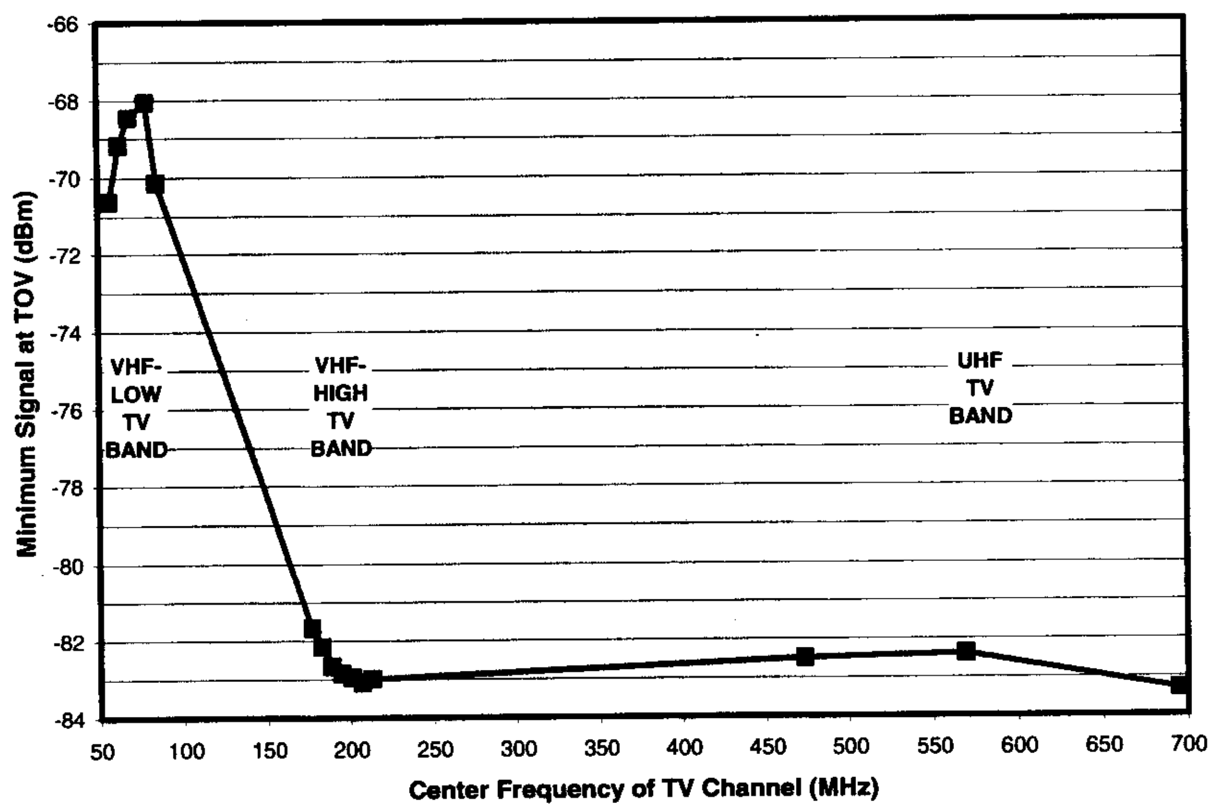

Figure 4-6. Measured Minimum Signal Level at TOV Versus Frequency for Receiver G2

CHAPTER 5
INFERRED NOISE FIGURE

The minimum signal level at TOV, presented in Chapter 4, can be viewed as the combined effect of two properties of the DTV receiver: the internal noise created by the receiver's input circuitry and the CNR required to produce a clean picture. Separating the measurement into those two basic terms provides a better understanding of the differences in performance between DTV receivers. It should be noted that this breakout is strictly valid only when reception sensitivity is limited by the receiver's amplifier noise, which we anticipate to be true for most receivers; however, if other factors limit reception sensitivity, the "inferred" receiver noise calculations in this chapter reflect those other performance limitations rather than actual receiver noise.*

The internal noise created by a receiver is often expressed in terms of noise figure. The noise figure of a receiver is the effective amount of noise created by the input circuitry of the receiver, measured relative to a physical limit on noise known as thermal noise and referenced to the input of the receiver. While noise figure cannot be directly measured externally, the effective noise figure can be inferred from the required CNR measurements of Chapter 3 in conjunction with the minimum signal level at TOV, as measured in Chapter 4.

Figure 5-1(a) illustrates measurement of required CNR (i.e., white noise threshold). The vertical line represents a range of signal and noise amplitudes that could be applied to the antenna terminal of a TV receiver. With external white noise added at a level well above the internal noise of the receiver, signal levels in the lower, red portion of the line will result in no TV picture. Signals in the yellow range will produce a picture degraded by demodulation errors. Signals in the green range, with signal level exceeding the noise level by an amount greater than the required CNR, will produce a picture free of reception-related defects. (The carrier-to-noise ratio (CNR), becomes a difference rather than a ratio, because of the logarithmic scaling implied by measurements in decibels.)

Figure 5-1(b) illustrates measurement of minimum signal at TOV, the minimum signal level required to achieve a clear picture absent any external noise. Assuming that the TV reception is limited by the receiver's broadband internal noise, this minimum signal level can be viewed as the sum (in dB) of two parameters—the internally generated noise level of the DTV receiver and the amount by which the signal must exceed that noise level, i.e., the required CNR. The noise level of the receiver can be expressed as the sum (in dB) of the noise figure of the receiver and the thermal noise at some reference temperature. Thus, we have

Minimum Signal at TOV (dBm) = Thermal Noise (dBm) + Noise Figure (dB) + Required CNR (dB)

Thermal noise is a function only of reference temperature and measurement bandwidth and is given by

$$\text{Thermal Noise (dBm)} = 10\log(k\,T\,B) + 10\log(1000\ \text{mW/W})$$

* Various receiver design anomalies could result in reception sensitivity being limited by factors other than receiver noise (noise figure). For example, if the AGC (automatic gain control) does not allow sufficient RF and IF gain to amplify a weak signal to the level necessary for demodulation, reception performance will be limited by gain rather than by amplifier noise. Similarly, receiver performance could also be limited by local oscillator phase noise or by leakage into the tuner of internally-generated interference sources such as impulse noise from digital circuits or narrowband (tonal) interference.

where

k = Boltzmann's constant = 1.38065 x 10^{-23} joules/°K
T = reference temperature in degrees Kelvin (290°K for this report)[*]
B = the measurement bandwidth = 6,000,000 Hz for a television channel
10 log(1000 mW/W) provides the conversion from dBWatts to dBmilliwatts

Using the above values, thermal noise = -106.2 dBm.

If the noise generated internally by the DTV receiver is similar to white Gaussian noise, then the required CNR in Figure 5-1(a) is the same as that in Figure 5-1(b); consequently, noise figure of the receiver can be computed as

Noise Figure (dB) = Minimum Signal at TOV (dBm) – Required CNR (dB) – Thermal Noise (dBm)

RESULTS

The noise figures for all tested receivers on the three tested channels have been computed as above and are shown in Figure 5-2. Individual results for TV channels 3, 10, and 30 are shown in Figures 5-3, 5-4, and 5-5, respectively. The general format of the plots is as described in Chapter 3 in the section titled, "Format of the Bar Graph Data", except that, in the case of Figure 5-2, there are three bars per DTV receiver—representing the three channels tested. The reader should note the differences in vertical scales among the four graphs.

Note that in performing the noise figure calculation, the required CNR is assumed to be constant across the TV channels for the reasons discussed in the "Effect of TV Channel" section of Chapter 3. Thus, the CNR measurements on channel 30 are applied to channels 3 and 10, as well.

Nominal Noise Figure and Variation Among Samples

Table 5-1 shows the statistical properties of the noise figure across all tested receivers.

Table 5-1. Statistics of Receiver Noise Figure

NOISE FIGURE	Chan 3	Chan 10	Chan 30
Median across all receivers (dB)	8.8	7.6	6.9
Median re OET-69 planning factors	-1.2	-2.4	-0.1
Deviations of receivers from median			
--Best performing receiver (dB)	-2.5	-1.3	-1.3
--Worst performing receiver (dB)	12.2	4.5	2.6
--89th percentile receiver (dB)	4.5	3.3	1.2
Standard deviation (dB)	3.6	1.6	0.9
Total span from worst to best receiver (dB)	14.7	5.7	3.9

The median noise figure across all measured receivers was found to decrease with channel—with the noise on channel 30 being 1.9 dB lower than that on channel 3. The median noise figures were 1.2 to 2.4 dB better than those shown in the OET-69 planning factors for the VHF bands (10 dB) and essentially matched the planning factor for the UHF band (7 dB).

[*] The reference temperature is generally taken as the antenna temperature. 290°K = 17°C = 62°F results in a thermal noise level matching the -106.2 dB value used in OET-69.

On channel 3, only 21 percent of the tested receivers performed more poorly in noise figure than the value modeled in OET-69 by an amount exceeding 1-dB—the approximate tolerance of the measurements.* On channels 10 and 30, the numbers are 7 percent and 18 percent, respectively.

The variations among receivers were large on channel 3—with a 3.6 dB standard deviation and two receivers performing at levels 10.3 and 12.2 dB worse than the median. More attention to tuner design for those two receivers might significantly improve performance in weak signal conditions. 89 percent of the receivers (all but three) were no more than 4.5 dB above (worse than) the median noise figure.

Variations were relatively small on channels 10 and 30. Standard deviation across all receivers was 1.6 dB on channel 10 and 0.9 dB on channel 30. The worst performers differed from the median by 4.5 and 2.6 dB, respectively, on channels 10 and 30, and 89 percent of the receivers (all but three) were no more than 3.3 dB above (worse than) the median noise figure on channel 10 and no more than 1.2 dB above the median noise figure on channel 30.

Variation With Product Type and Price

Magnitude of Observed Variations With Product Type and Price

As can be seen in Table 5-2, the observed variations in receiver noise figure with product type and price categories were very small (category medians differing from overall median by less than 1 dB) for channels 10 and 30 and were somewhat larger for channel 3. On channel 3, median noise figure of set-top boxes was 1.7 dB worse than the overall median of all receivers. The best median noise figure—1.4 dB better than the overall median—occurred in the low-price DTV category. Such differences are likely to influence performance only in locations where the signal margin is very small.

Table 5-2. Product-Type/Price Variations of Receiver Noise Figure

NOISE FIGURE	Chan 3	Chan 10	Chan 30
Median of Set-Top Boxes re Overall Median (dB)	1.7	0.1	0.6
Median of Low-Price DTVs re Overall Median (dB)	-1.4	-0.1	0.0
Median of Medium-Price DTVs re Overall Median (dB)	0.0	0.4	-0.1
Median of High-Price DTVs re Overall Median (dB)	-0.8	-0.3	0.0

Statistical Significance of Observed Variations With Product Type and Price

Table 5-3 shows the Pearson's correlation coefficient between the noise figure and the price of each DTV receiver. Given the similarity of results with those for minimum signal at TOV, the reader is referred to Chapter 4 for a discussion of the interpretation of these results. The bottom line is that there is no statistically significant correlation of noise figure with price of the receivers..

* Absolute measurement accuracy of the vector signal analyzer on the amplitude range that was used for the measurements was as ±1.5 dB maximum and ±0.5 dB typical.

Table 5-3. Correlation Coefficient of Receiver Noise Figure with Price

Pearson's Correlation Coefficient of Noise Figure with Price	Chan 3	Chan 10	Chan 30
All Tested Receivers	-14%	-4%	+6%
DTVs Only (no Set-Top Boxes)	-1%	-1%	+11%

Relative Variations in Noise Figure and Required CNR

Figure 5-6 shows the required CNR for each receiver as a function of noise figure on each of the three tested channels. Contour lines can be used to read the combined effect of the two parameters on minimum signal at TOV. It is clear from the plot that most of the variation in receive sensitivity (i.e., minimum signal level at TOV) of the DTV receivers is due to variations in receiver noise figures rather than variations in the CNR required by the demodulator. In fact, based on standard deviations of the parameters, variability in noise figure among the receivers is 4.2 times as high as the variability in required CNR on channel 30, where the noise figure variations are smallest. On channels 10 and 3, respectively, the noise figure shows 7 and 16 times the variability of required CNR.